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A NON DESTRUCTIVE TESTING PROGRAM FOR A GROUP OF JET GROUTING COLUMNS

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SYNOPSIS

An extensive soil improvement program was developed for the Voltri Container Terminal, Italy, located on an Hydraulic Reclamation Fill. The Office and Warehouse Building, and the Light Tower foundations were supported by Jet Grouting Columns. A testing program was developed, including coring and nondestructive testing on the columns, to verify the as built conditions. Test results show the difficulties in evaluating Jet Grouting properties with a nondestructive approach, mainly related to the complex geometry of the columns. However, the analysis and the comparison of the wave records provided suggestions on the most effective testing procedures, and on the possibility of estimating the variation in column diameter.

KEYWORDS

Jet Grouting, Non Destructive Testing, Echo/Impulse testing, Parallel Testing, Load Testing.

INTRODUCTION

The Voltri terminal was described in a previous paper presented to the third case history conference in St. Louis (Varosio et Al., 1993).

The tamping operations included more than 300000 blows, using falling weights of 10 to 15 tons, dropped from heights of 10 to 15 meters, and prints with typically 10 blows each.

Since the start of operations in 1995, there have been negligible pavement settlements. Despite the very poor initial conditions of the hydraulic fills, the tamping method proved to be an effective, low cost, and low time consuming improvement method for the site.

The building area of the plant (Figure 1) was constructed during the initial phases of fill placement by dumping rubble from trucks. In this area no tamping was performed, and the Office and Warehouse buildings were designed using continuous footings on jet grouting columns.

The 24 Light Towers in the terminal area were also founded on jet grouting, with four columns beneath each footing. Part of these towers are located in the area treated by tamping. Some of them however, particularly those located on the oldest fills, were founded on Jet Grouting Columns in uncompacted soils.

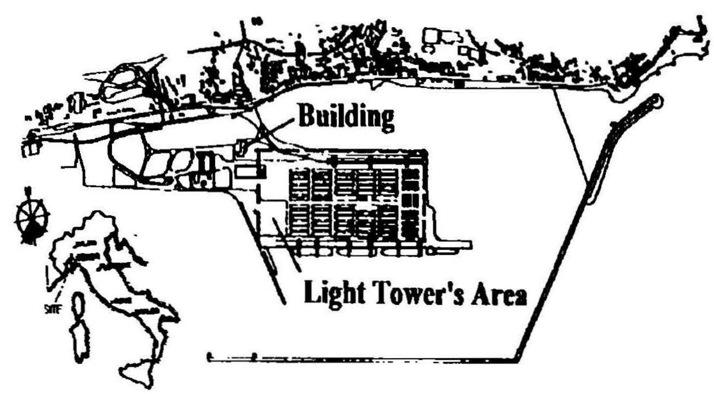


Fig. 1. Site view

Due to a modification of the plant layout, construction of the subject building was delayed, leaving the Jet Grouting columns uncovered for a period of time. This gave the possibility to verify in detail the columns properties.

Initial coring of the columns indicated that cementation apparently did not extend down to the design base. Thus an extensive program of nondestructive testing was promoted by both the Owner and the Contractor in order to reach an agreement on the actual dimensions of the columns.

The testing program for this jet grouting work has included:

- 1992: grouting field test to determine attainable column diameters; load tests on grouted columns.
- 1994: column coring and impulse testing to determine as built length.
- 1995: parallel testing (hydrophone in boring adjacent to columns) to measure column length.
- 1996: further parallel testing with full wave form recordings. The 1995 and 1996 tests were made by COLMAR, of La Spezia, Italy.

SITE AND SOIL CONDITIONS

The plant is sited on a reclaimed area which required over 10 million cubic meters of fill, with an average thickness of more than 15 meters. The fill was mainly built with dredged soils. Part of the fill, mainly in the west portion, was dumped from trucks. About 300,000 square meters of the plant were compacted by tamping. The prints were filled with granular coarse selected materials. Prints were typically 2.5 meters apart, on two 5 m. grids. This improvement method has left a typical leopard-skin patchwork at the surface, later covered with a multi-layer pavement (Varosio et Al. 1995).

The post tamping moduli, derived from the penetration tests and checked by means of large diameter plate tests, were approximately 5 MPa within prints.

The jet grouting columns at the base of the Light Towers were built after tamping operations; an obvious precaution to avoid damages to the columns. These columns were thus formed in an heterogeneous environment, with no practical possibility of evaluating the presence, location and size of the filled prints at the grouting points.

Some Light Towers, like the Warehouse and Office Building, were located on rubble fills, dumped from trucks, not compacted by tamping. The soil profile at the location of the building is shown in Figure 2. The initial sea bottom level corresponds to the transition from the dumped heterogeneous fills to the fine dark gray silty sands. This last formation lays above the weathered serpentine bedrock.

The bedrock is covered at the boring location by a thin layer of soft silty clay. In order to provide a clean contact with rock, it was specified to drill with the jet rod for at least one meter inside the bedrock.

SPT's were performed to measure the fill and soil properties (Figure 2). At rubble fill locations where tamping was performed, Menard pressurometer tests were also carried out, before and after the soil improvement, in order to verify the compaction results. Typical initial values of moduli were very scattered, with minimum values of less than one MPa.

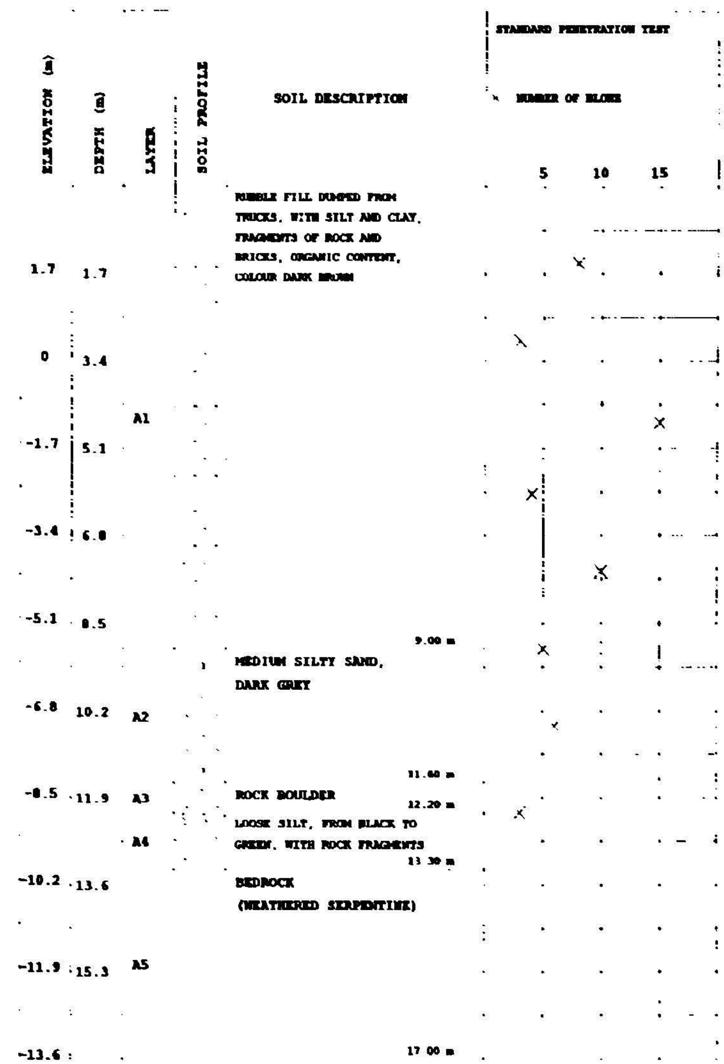


Fig. 2. Soil profile in the building area.

The water table at the building location was slightly above the sea level.

FOUNDATIONS FOR BUILDING AND TOWERS.

Generally speaking, the behavior of soils improved by jet grouting is not yet completely understood, with different points of view within the professional community. Contractors usually claim that the jet grouting columns behave like single bearing columns. They should be thus designed like foundation piles, and, according to applicable regulations, some experimental columns should be tested, to verify the required safety factor.

However, when this approach is proposed by the designer, the similarity with bearing piles is usually abandoned, and the jet grouting method is preferably compared to more conventional injection methods. The behavior of improved soils is then interpreted more in terms of mass behavior, than in terms of single bearing elements.

In the Voltri case however, the assumption that columns would behave as single bearing elements prevailed. Accordingly, field and load tests were scheduled.

A plan view of part of the building foundations is shown in Figure 3, with grade beams founded on jet grouting columns. A design load of 350 kN was considered for each column; a nominal diameter of 60 centimeter will produce a working stress of about one MPa. Four columns of the same diameter were also designed for the foundations of the Light Towers.

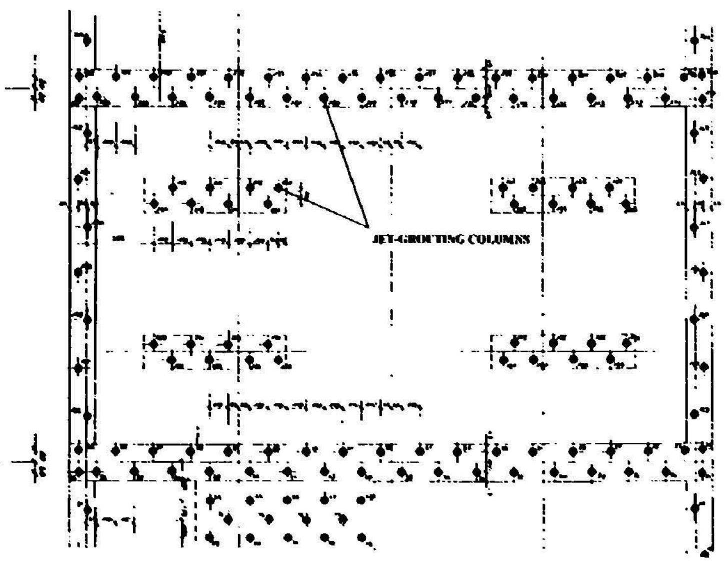


Fig 3. Building foundation's view

The average design length of the column for the building was 14 meters, such to have the column base in contact with the bedrock. A length of 16 meters was scheduled for the tower foundations, intended to penetrate the silty sand of the original sea bottom by 6 m.

JET GROUTING FIELD TEST

The field test was located in the building area (Figure 4). The jet grouting parameters were modified during column grouting according to the range of values given in Table 1. Columns heads were later cleaned to measure the diameter (Figure 5).

The column head was adapted to the load test by means of a pipe casing of 600 mm. of diameter, used to form a concrete capital suitable to provide the base for the jack. The final test load was two times the design load . This follows the Italian national regulations, which allow a safety factor of two when load tests are performed. Load test data are shown in Figure 6.

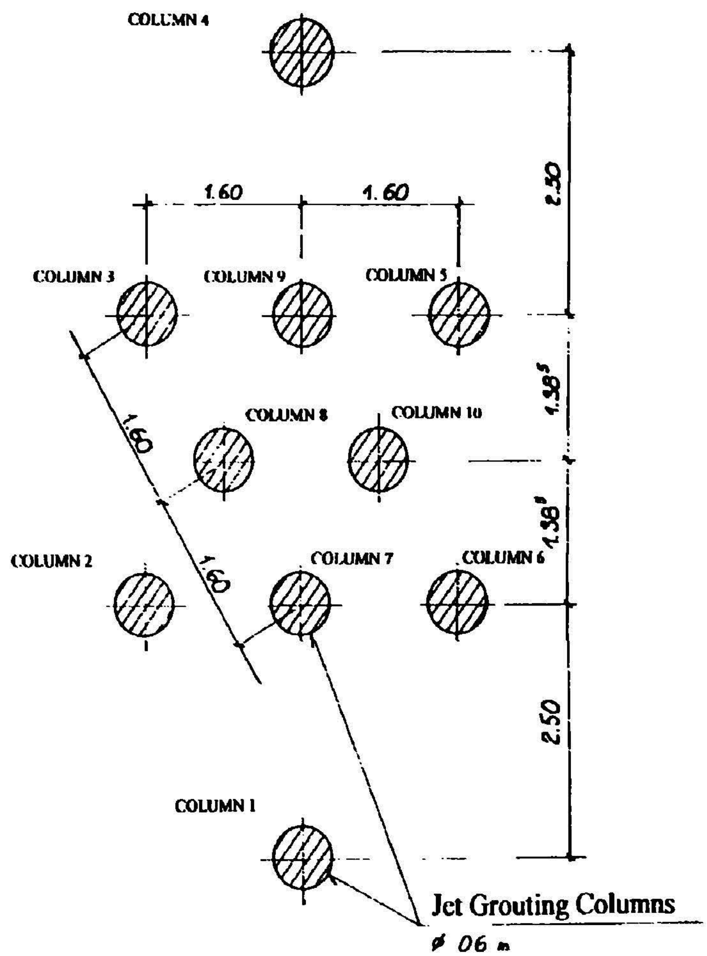


Fig. 4. Jet Grouting Test. Plan View

Item	Data
Jet grouting type	Monofluid
Column length (m)	13.50 - 14.50
Nozzle diameter (mm)	1.6 - 2.0
Withdrawal time step (s)	8 - 14
Grout pressure (MPa)	40
Cement/water ratio	0.65
Grout weight (KN/m)	1.4 - 3.0
Cement type	325

Table 1. Field test. Jet grouting parameters.

The column performed as a load bearing member, and the foundations could be directly placed on the columns, without the need of columns located outside the foundation imprint.

Fig. 5. Excavations to clean a column head

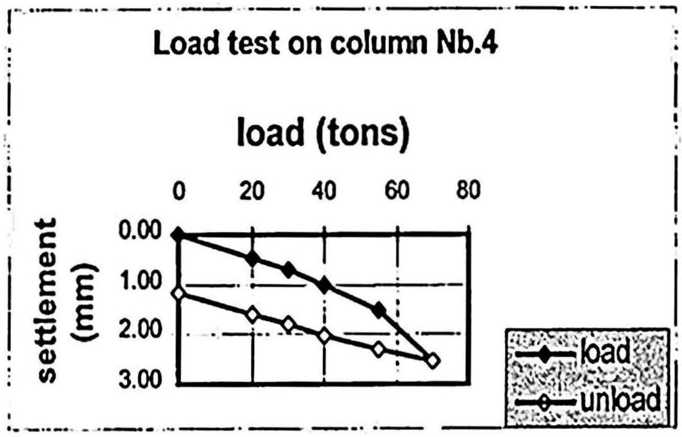


Fig. 6. Load test data.

COLUMN CORING

After jet grouting works, to check as built conditions, as all columns were accessible from the surface, coring was deemed to be the simplest way to verify the jet grouting depth.

The columns were cored using a 4 inch diamond bit. The maximum length of cemented cores recovered was six meters. The same length was found also for a column of the field test, made under strict observation by both the Designer and the Owner.

Close inspection of the samples indicated the possibility that coring went out from the columns, as suggested by the diagonal cut at the base of the cemented samples. The Owner did not agree with this conclusion, however, and additional non destructive testing to verify the column lengths was scheduled.

In view of evaluating the nondestructive testing data, unit weights of some of the cores were measured in the field lab. The range of unit weight values resulted to be 18-25 kN per cubic meter, consistent with the wide variability of the fill.

ECHO/IMPULSE METHOD

Echo/Impulse tests were performed on 15 columns. Prior to testing the column heads were excavated and all loose material was removed.

A typical layout of the Echo/Impulse test is shown in Figure 7.

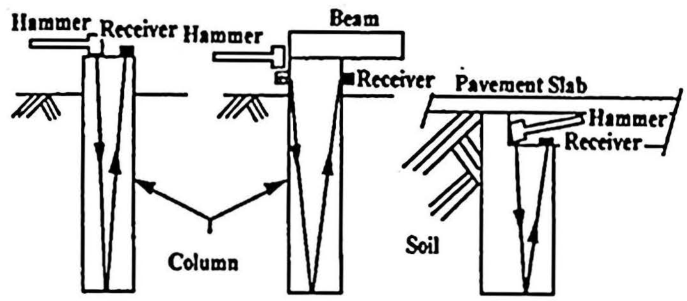


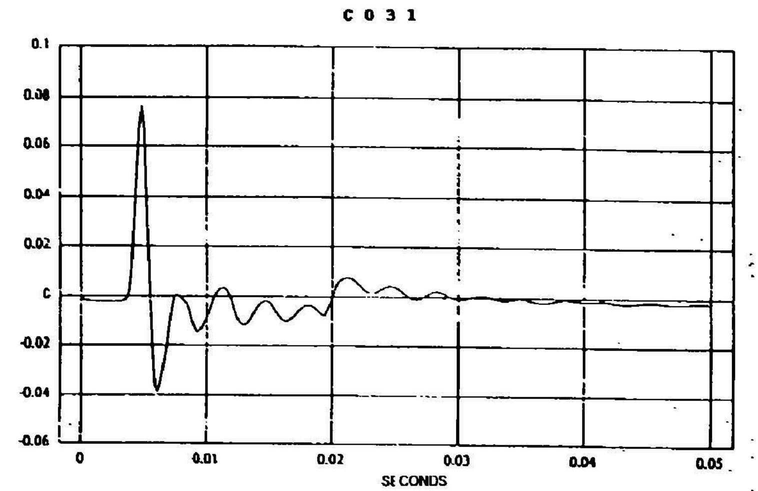
Fig. 7. The Echo/Impulse test (After Olson Eng. Inc.)

The echo/ impulse method generally in use to test jet grouting columns is based on the same principle of the vibrational methods used for foundation piles. The column is impacted with a hammer, with an accelerometer glued to the head of the column. An analysis of the recorded time history provides information on column geometry and performance.

For the case of piles, the geometry is usually sufficiently regular to allow a Fourier transform of the vibration records, that can be more easily used to derive information on the quasi-static stiffness of piles, and the nature of the contact of pile shaft with the bearing soil.

The strong variability of jet grouting columns usually prevents the evaluation of responses in the frequency domain. Previous experience has indicated that responses transformed in the frequency field are too irregular and scattered to be interpreted.

The response in the time domain is however in most cases sufficiently clear. Vibration time histories measured in the subject case are shown in Figure 8.



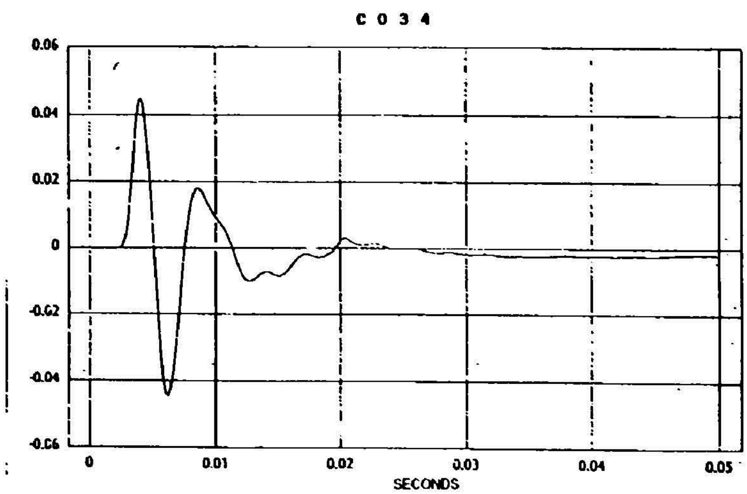


Fig. 8. Echo/Impulse test data

To evaluate the column length, a measure, or an assumption on the column compression wave velocity is required. As ground water is very shallow at the site, it was impossible to directly measure wave speed in the column. The variability of the grouted material would make furthermore such measurements difficult in any case. Also the columns cores previously obtained were too short to allow a reliable measure of wave velocity.

The range of reference compression wave velocities, 1900-2200 meters per second, was thus defined on the basis of previous experience on similar soils, treated with the same monofluid method.

The knowledge of the actual compression velocity of Jet Grouting columns appears to deserve more future research, related as it is not only to the variable nature of soils, but also to the alternative methods of Jet Grouting (mono, bi, or three fluid, with a wide range of design parameters).

To give an example, for a three fluid jet grouting work in a fill that could be apparently considered to be equivalent to this fill, velocities between 2800 and 3000 meters per second were assumed by other operators, closer to the velocity of reinforced concrete piles. For the Voltri case however, higher velocities would have been in contrast with the length given by the presence of the bedrock at about 15 meter of depth.

The tests provided an estimate of column lengths as shown in Table 2.

Column Nb.	Reflected Arrival (ms)	L1 V1=1900 m/s (m)	L2 V2=2200 m/s (m)	early arrival ms	L3 (m)	L4 (m)
21	15.4	14.6	16.9	4.6	4.4	5.1
28	15.4	14.6	16.9	4.7	4.5	5.2
31	15.8	15.0	17.4			
34	16.0	15.2	17.6	4.8	4.6	5.3
42	15.5	14.7	17.0			
45	15.5	14.7	17.0			
51	15.4	14.6	16.9			
172	15.4	14.6	16.9			
174	15.4	14.6	16.9	4.2	4.0	4.6
177	15.0	14.2	16.5			
185	17.0	16.2	18.7	5.4	5.1	5.9
188	14.6	13.9	16.1	3.8	3.6	4.2
191	14.4	13.7	15.8			
195	16.2	15.4	17.8			
204	15.6	14.8	17.2	4.8	4.6	5.3

Legend: L1 and L2 = full length of columns for velocities V1 and V2. L3 and L4 = depth of possible anomalies for the same velocities.

Table 2. Echo/Impulse tests summary

Lengths correspond generally to the design values. Anomalies were disclosed for some columns at a depth close to the transition zone from the fill to the in situ seabed soils. These soils are finer than the heterogeneous fill, and the column diameters are expected to be lower than above, with a possible reflecting surface in the transition zone.

These anomalies are not expected to reduce significantly the bearing capacity of the columns. An extension of the testing program, with alternative methods, was scheduled nevertheless.

PARALLEL TESTING. 1995

For some columns of the same group an alternative non destructive testing method was used in 1995, as shown in Figure 9.

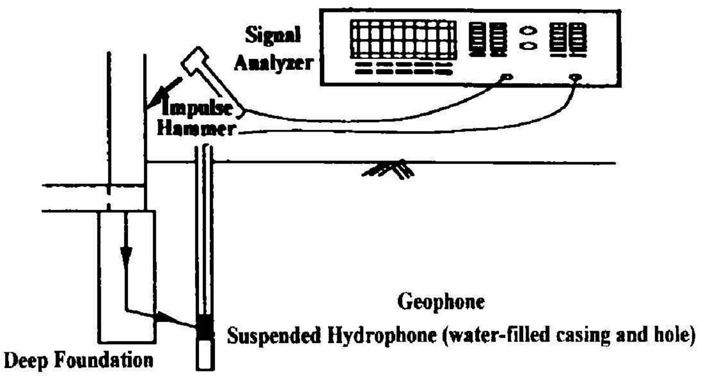


Fig. 9. Parallel testing layout (After Olson Eng. Inc.)

A wave was induced by striking the columns with a light hammer. The response was measured by a hydrophone in a water filled boring nearby. As the sensors were in water, only compression waves could be recorded. The vibration propagation in columns and soil however may also have included shear wave components. Some typical records of this test are shown in Figure 10, with points related to the first arrival of waves. The change in slope was interpreted by CO.L.MAR as the transition from waves propagating in the columns to waves propagating in the soil below. The corner point was therefore considered as an indicator of the length of the column. It was concluded that 9 columns were shorter than the design length, and that two columns were discontinuous at some location above the column base, as indicated in Table 3.

It is of interest to note that two of the columns tested in 1995 were previously tested by the Echo/Impulse method, with a length evaluation between 15.0 and 17.6 meters. For Column 34, or Nb. 6 of Table 3, (Figure 6 and 10), the anomaly disclosed at a depth from 4.6 to 5.3 meters by the Echo/Impulse method was interpreted as the column length on the basis of the parallel testing. Column Nb.9 (31 for the previous test, Table 2) resulted to have a length of 12 meters, to be compared with a length of more than 15 meters evaluated by the Echo test.

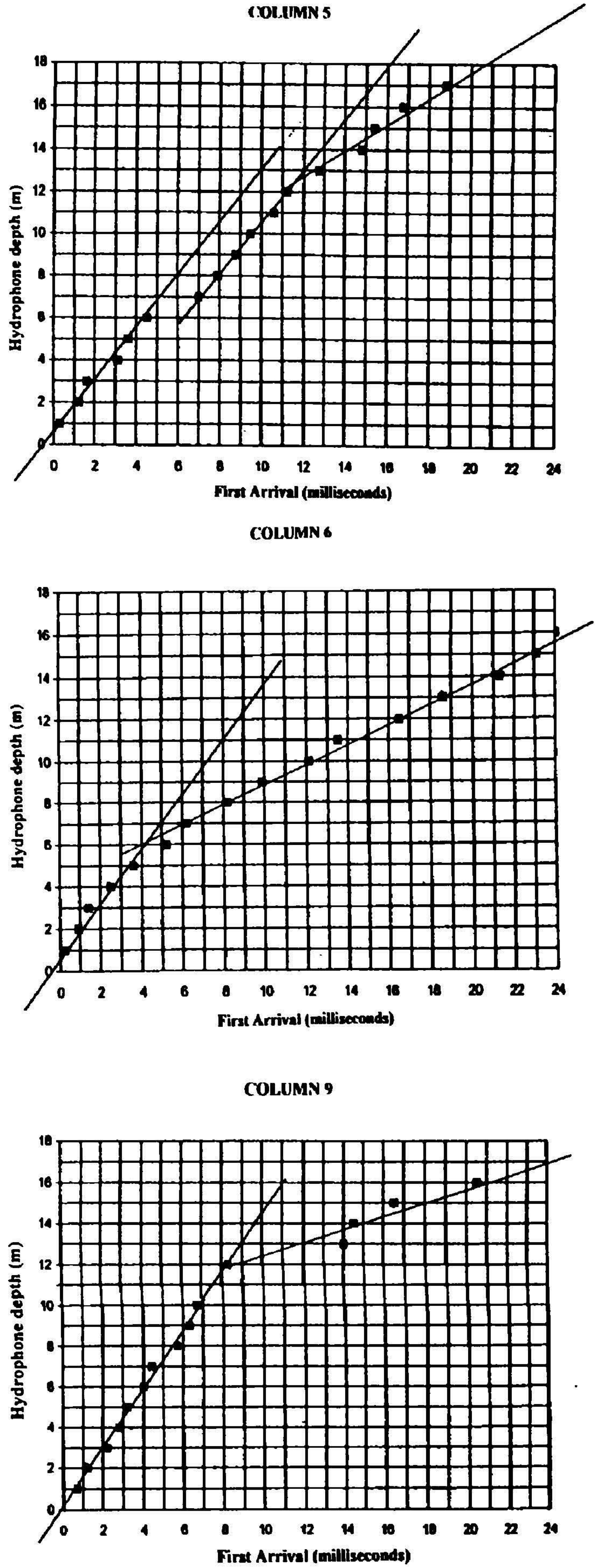


Fig. 10. 1995 Parallel testing. First arrival data

Column Nb.	Column Length (m)
1	8
2	6
3	> 8
4	6
5	12 with a defect at 6 m.
6	5 to 6
7	6
8	17 with a defect at 3 m.
9	12
10	7
11	17

Table 3. Evaluation of 1995 parallel testing

The possible diameter reduction for column Nb. 6 (34), due to the transition to a finer soil, may have produced the discontinuity of wave arrivals of Figure 10. The presence at that depth of a annular surface, due to the diameter variation, may produce vibrations propagating in the soil, that mask arrivals from lower levels of the columns.

The wave velocities measured with this test do not correspond to the compression velocities used in the evaluation of the Eco/Impulse test.

Considering a compression wave velocity of 1900 to 2200 meters per second, and a Poisson ratio of 0.3, a range of shear wave velocities of 1180 to 1360 meters per second can be estimated. This is not far from the first arrival values of the fastest waves shown in Figure 10. CO.L.MAR. interpreted these differences as the difference between bulk and normal velocity modes.

The arrival of the slowest waves can be related to compression waves propagating in the soil, possibly modified by the presence of the columns.

Quite surprisingly, no compression wave velocities close to that of the water were measured during these tests. This measure was made during the 1996 testing, with source and sensor lowered in the same hole, and the correct velocity of about 1500 meters per second was measured.

It may also be inferred that the shift of the record of Column 5 of Figure 10, between column sections with the same velocities, could be related to the change in column diameters mentioned above.

A shear wave velocity of 100 meters per second, consistent with some soil compression wave values discussed in the following chapter, would indicate a diameter variation of 10 to 30 centimeters for the Jet Grouting columns, related to shifts of one to three milliseconds.

Although a conclusion on this aspect cannot be reached on the basis of only the subject tests, if local soil shear wave velocities are measured, this approach could allow estimates of columns/pile diameter variations.

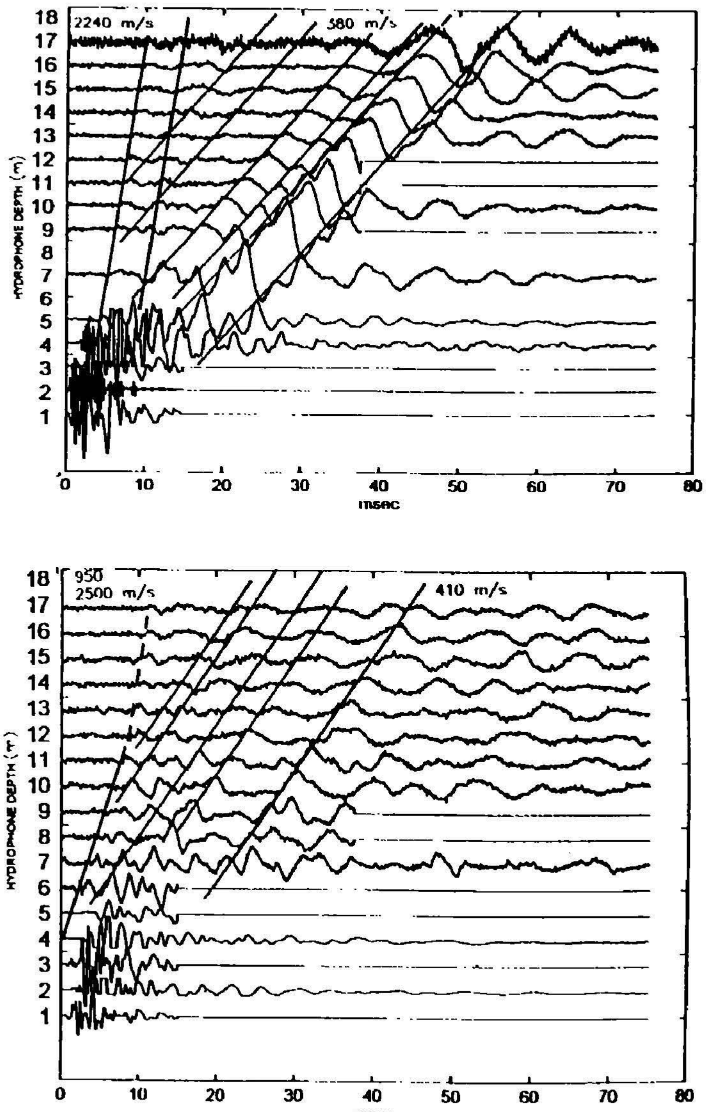


Fig. 11. Parallel testing. 1996

PARALLEL TESTING. 1996

Due to the contradictory evaluations of column properties shown by the tests of 1994 and 1995, an additional testing program was performed in 1996. This final testing was made evaluating the complete time history of induced vibrations, a more refined method than the first arrival approach of 1995.

The same experimental setup was used, and the impact wave induced in the foundation was measured in an adjacent parallel boring. In this case however, the complete time history of the vibrations was recorded and interpreted.

By this time construction had progressed at the site, and the Jet Grouting columns were no longer exposed. In the building area the columns were covered by a pavement and at the light towers the foundation had been cast over the groups of columns.

Tests were performed in the building area, the site of the 1994 and 1995 tests, by hammering on the pavement above the columns. Results are not presented here. Similar tests were also carried out for the foundations of two Light Towers Nb. 24, located in an area compacted by tamping, and Nb. 4, located in an area of loose dumped fill. For this test a falling weight was allowed to impact the foundation based on 4 Jet Grouting columns.

The impact of the falling weight on the foundation induces a sonic wave in the grout columns below, but also in the surrounding soil and even in the nearby monitoring boring casing. The intent of the test is to identify the wave traveling in the grout, and use it to verify the column length. The presence of the other media complicates the issue.

Some of the wave records measured are shown in Figure 11. Three ranges of velocities were measured:

V1= 2240 to 2500 m/s.
V2= 930 to 1030 m/s,
V3= 330 to 410 m/s, and

It can be observed from Figures 11 that the wave arrivals corresponding to the highest velocities are partially masked by the slowest waves. The absence from measures of values corresponding to waves propagating in water can be also explained by a complete hiding of their arrivals.

Surprisingly enough, the 930-1030 m/s velocity range can only be related to waves propagating in the PVC casing of the holes in which the sensors were lowered. For these pipes the following properties were given by the supplier:

Elastic modulus = 2.5 to 3.0x 10^3 MPa
Unit weight = 15 KN/m^3
Poisson ratio = 0.25 to 0.30.

With these values, a maximum Compression Wave Velocity of 1400m/s and a minimum Shear Wave Velocity of 790 m/s can be computed, including the velocity range measured with the parallel testing.

An estimate of soil compression wave velocities based on the SPT data shown in Figure 2, with a possible static modulus between 20 and 30 MPa, and a compression dynamic modulus estimated to be 130 to 200 MPa, has indicated a velocity range of 310 to 380 m/s, not far from the lowest velocities. These tests apparently measured the soil compression wave velocities; no observations could be correlated to compression wave velocities of the water, that are usually expected to hide the lower velocities of soils.

The highest velocities range can be related to waves propagating in the Jet Grouting columns with values slightly higher than the values of the Echo/Impulse tests. The deepest point of intersection between high velocity and low velocity waves was interpreted by CO.L.MAR. as corresponding to the depth of the bottom of the column.

CONCLUSIONS

The testing program described above has shown how difficult can be to verify geometry and properties of jet grouting columns. The Echo/Impulse test required assumptions of the propagation velocity of compression waves in the columns. These velocities were not completely confirmed by the parallel testing approach. The velocities measured with the parallel method, although carefully verified, are difficult to relate to a physical model of wave propagation.

The parallel testing may also provide an estimate of column diameter's variations, and, in perspective, of the column diameter. A verification of this possibility will require detailed measures of soil wave velocities in contact with the columns.

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